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The purpose of this research was to investigate alternative gun seals for Cased Telescoped Ammunition (CTA). This report summarizes the research findings of the 6-month duration project. The Army topic description for this research (#A01-001 of the 2001 DoD solicitation) called for an investigation of the suitability of smart materials for this application. One such smart material mentioned by the Army in the solicitation was Nitinol, a shape memory alloy. MSI has developed and performed a thorough theoretical investigation of potential CTA sealing concepts that utilize this material. MSI also has investigated other concepts such as Teflon rings, piston rings, rubber skirts and nylon coatings. Several prototypes that fit a 145mm cartridge were manufactured. A Nitinol sealing concept was developed that, based on theoretical evaluation, should provide excellent sealing performance. The design was based on currently available metal c-rings. A cost-effective manufacturing method was also established and a potential vendor was identified.

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Msi Technical Report TR-81801

Cased Telescoped Ammunition
Smart Seal Development
SBIR Phase I Contract # DAAE30-02-C-1029

By: William J. Kelly and William D. Marscher
Aug 5, 2002

Prepared for: US. Army TACOM-ARDEC

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Mechanical Solutions, Inc.
Engineering Analysis, Test & Technology

Msi Summary Report TR-81801

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SBIR Phase I Contract # DAAE30-02-C-1029

By: William J. Kelly and William D. Marscher
Aug 5, 2002

Prepared for: US. Army TACOM-ARDEC

EXECUTIVE SUMMARY

Mechanical Solutions, Inc. (MSI) was awarded a DoD Phase I, Small Business Innovative Research (SBIR) Contract by the US Army. The purpose of the research was to investigate alternative gun seals for Cased Telescoped Ammunition (CTA). This report summarizes the research findings of the 6-month duration project.

The Army topic description for this research (#A01-001 of the 2001 DoD solicitation) called for an investigation of the suitability of smart materials for this application. One such smart material mentioned by the Army in the solicitation was Nitinol, a shape memory alloy. MSI has developed and performed a thorough theoretical investigation of potential CTA sealing concepts that utilize this material. MSI also has investigated other concepts such as Teflon rings, piston rings, rubber skirts and nylon coatings. Several prototypes that fit a 145mm cartridge were manufactured.

A Nitinol sealing concept was developed that, based on theoretical evaluation, should provide excellent sealing performance. The design was based on currently available metal c-rings. A cost-effective manufacturing method was also established and a potential vendor was identified.

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INTRODUCTION

The Future Combat System (FCS) Science and Technology Objective is to develop technologies to provide revolutionary lethality through advanced direct and indirect armament systems using advanced propulsion systems for the Objective Force. The Objective Force Capabilities must be responsive deployable, agile, versatile, lethal, survivable and sustainable at an affordable cost. Cased Telescoped Ammunition (CTA) can support these objectives when combined with lighter ammunition-feed swing chambers, and smaller ammunition storage bins. However, technical obstacles have blocked the widespread application of CTA to date. The most important of these obstacles is the complete sealing of propellant gases at the fore and aft of the cartridge during firing, which had not been achieved prior to this SBIR project.

Smart materials, in particular shape memory alloys, have the potential to address the sealing problem. These materials, in particular Nitinol, have been applied liberally in bioengineering but have not been used or investigated as seal materials for CTA applications. The superelastic capability of Nitinol makes it an ideal candidate for a gun tube seal which must undergo significant radial expansion during firing. Its shape memory behavior can also be exploited.

As part of the seal development research effort, MSI was to develop and perform a thorough theoretical investigation of potential CTA sealing concepts that utilize Nitinol. In particular, a Nitinol C-Ring Seal (NICRS) concept that was conceived early during the project work was to undergo theoretical evaluation, to determine whether or not it would provide superior sealing performance. The design configuration was to be based on configurations with a high likelihood of near-term success (and thus able to support FCS goals), such as currently available COTS metal c-rings. A cost-effective manufacturing method was to be established, and a credible potential vendor was to be identified. In developing the design, extensive finite element analysis was to be performed.

In addition to the Nitinol concept, additional seal designs that showed promise were also to be conceived and evaluated. A Teflon ring design and a piston ring design were conceived, analyzed, and prototype manufactured, as detailed herein. Also discussed in this report are analytical results for a more conventional sealing concept consisting of a rubber skirt.

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DESIGN CONCEPTION, EVALUATION AND DOWN-SELECTION

Of the eight different concepts MSI has considered, five specific seal designs were down-selected as potentially viable. The remaining three concepts were determined by analysis to have one or more unacceptable characteristics unlikely to be sufficiently improved upon further development. Specifically, the Phase I proposal's concepts referred to as Smart Chevrons or Smart Wedges were de-selected based on a Biot-Fourier heat transfer transient conduction analysis. This analysis indicated that there would be too much blowby while the Nitinol material went through its temperature-actuated shape change. Likewise, the Phase I proposal concept referred to as the Smart Bellows was de-selected because structural analysis indicated the strong likelihood of either bellows rupture by the sudden application of the high pressure combustion blowby gases, or of jamming due to bellows warpage.

The tradeoffs of the remaining five designs evaluated as viable are summarized below in Table 1.

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Table 1: Advantages vs. Challenges for CTA Feasible Seal Concepts

Design Concept	Pros	Cons
1) Nitinol C-Ring Seal	Proven geometry for high-performance sealing Properties environment insensitive Dimensionally stable Insertion without radial split Superelastic springback to aid in cartridge extraction Corrosion resistant Wear resistant	High Raw Material Cost (This is being successfully addressed) Welding and Forming Methods need to be optimized (Part of Phase II effort, building on experiences of contractor APC)
2) Teflon/Shape Memory Plastic Ring	Smooth surface for insertion and extraction Can potentially be stretched and inserted into a non-split cavity Plastic shape conforms closely to degraded bore sealing interface	Plastic is much less dimensionally stable than metal Humidity can affect properties Embrittlement at low temperatures Subject to handling damage May melt & deposit onto bore
3) Piston Compression Ring	Proven technology in combustion engines Low Cost	Not proven for artillery applications; may jam and mar gun bore surfaces May not seal without lubrication Large bore deformations may present problems Leakage from radial gap
4) Plastic Coating Forward/Aft Seal	Plastic shape conforms closely to degraded bore sealing interface Reasonable cost (under $10) Some success in ballistic testing	Dimensional stability Humidity can affect properties Potential embrittlement at low temperatures Tight tolerance must be kept on outer diameter of plastic Metal/plastic interface must be optimized Secondary machining is required to hold tight tolerances Ease of damage due to handling
5) Rubber Skirt	Highly conformable to gun tube Already used on conventional Tank ammunition Reasonable cost (under $10) Some success in ballistic testing	Rubber is less dimensionally stable than metal Humidity can effect properties Potential embrittlement at low temperatures Tight tolerance must be kept on outer diameter of rubber Possible bonding issues

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The Concept 1 is MSI's NICRS (Nitinol C-Ring Seal) design and is an iterated version of one of the concepts put forth in the Phase I proposal, specifically the design referred to as the Inclined Plane. It was determined by the finite element analysis (FEA) simulations that the use of a two-piece seal was an unnecessary complication, and that a single piece seal could accomplish the same blast-pressure-energization intent of this seal. This was achieved by forming the flat sealing element into a curved cross-section, and subsequent tilting of the cross-section of the thin member so that the concave surface of the C-shaped hoop would face the incoming combustion gases. The C-shape also allowed the seal to be lightly spring-loaded against both the inner diameter of a shallow cartridge groove as well as the swing chamber wall, prior to firing. This would prevent any escape of combustion gases in the early stage of combustion and potential blowby. As combustion pressures increase, thereby increasing the pressure drop across the seal and encouraging leakage, the C-shape deforms axially against the cartridge groove wall, and radially against the swing chamber bore. A thin malleable coating encourages the seal to intimately seat against the swing chamber, even if the swing chamber has become scored by use. The cartridge groove is placed in a thick-walled area where its presence does not degrade the structural integrity of the cartridge. Since the cartridge under development is a new design, there also will be no need to back-fit existing inventory with grooving.

Using an appropriate thickness, FEA (finite element analysis) of the NICRS design showed that the ring would conform to the cartridge groove shape and form a good seal against a relatively smooth swing chamber without danger of extrusion (if the swing chamber or gun tube is not smooth, the coating would plastically flow to fill in the grooves and/ or thin gaps). The superelastic behavior of Nitinol would then encourage the seal to return to shape at the end of the firing process, thereby preventing jamming during extraction. In addition, either the shape memory or superelastic properties or Nitinol can be employed to significantly "stretch" the ring during assembly, so that the ring can be slipped over the end of the cartridge, and then "snapped" into its groove. This avoids the need to split the ring, or to have a removable (and therefore expensive to assemble) casing end piece. The current C-shape was chosen with simplicity of manufacturing in mind. In addition, the simple C-shape cross-section is similar to currently manufactured non-Nitinol seals, for which manufacturing procedures are already in place. Nevertheless, the use of Nitinol will present some interesting challenges with regard to produce-ability and cost. Later in this report, MSI will discuss the proposed Phase II work to investigate and apply flame-spray methods for Nitinol thin-strip material production at greatly reduced cost, and to convert the APC (MSI Phase II seal fabrication contractor) trim-and-weld methods from its current Inconel fabrication successes to Nitinol fabrication. Phase II success in these areas will allow for low-cost and practical Nitinol C-Ring production.

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C-ring seals offer very high reliability and excellent performance, as a result of their simple, symmetrical and therefore elegant design. Sealing is achieved using the strain energy of the element compressed into the bore, augmented by the forces due to the pressure acting upon the annular space in the cartridge/ gun bore clearance gap. Existing commercial-off-the-shelf (COTS) C-ring seals are frequently electroplated to provide a ductile sealing surface able to conform to the surface imperfections and asperities in the mating hardware, and therefore such plating is a known art. Obtaining an adherent coating to a new material application such as Nitinol, however, should not be taken for granted, and will form part of the Phase II investigation.

The Concept 2 is an enhanced variation of the Phase I proposal idea referred to as "Smart Foil-Shielded Plastic". It also incorporates the self-actuating nature of the C-shape cross-section. Similar COTS designs are currently manufactured using industrial plastics such as Teflon. The blast-shielding foil or the plastic, or both, would be made of shape memory material, to enhance their contraction ability following the firing process. Both energization and later extraction would be further aided by a hoop spring which runs through the center of the seal, as described further below.

The Concept 3 is a version of the Phase I proposal idea referred to as Smart Piston Rings. The concept can act in the same way as a typical piston compression ring for a reciprocating engine. Manufacturing it in part or entirely out of Nitinol could enhance its tendency to spring-back and reduce the chances of jamming the gun during extraction. A zero-emission gap can be utilized based on off-the shelf ring gap technology (as explained further below), as a further enhancement to the piston compression ring, although such a gap would increase production costs.

The Concept 4 is a Nylon 11 plastic coating to be placed over the surface of the forward and aft sealing areas. The nylon would be deposited on the metal surface to provide a compliant interface with the swing chamber bore.

The Concept 5 is a rubber skirt similar to that used in previous tank cartridge sealing systems. The skirt is to be molded to the edge of the metal forward and aft sealing areas. During firing the skirt expands to seal the axial blowby.

Of all the above designs the most likely to meet and surpass the ARDEC performance requirements is the NICRS Nitinol C-Ring Seal. This is based on the fact that the seal's advantages outweigh its development challenges. It provides complete sealing from the initiation of combustion, strongly encourages extraction, is made of a high strength/ wear resistant/ corrosion resistant metal that can stand up to environmental effects, and has the potential to become the lowest cost of the seal concepts under consideration. Its elegant and

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simple C-shape design provides for feasible cost effective manufacture of the product. Its superelastic properties allow it to withstand the large bore expansion that occurs during firing better than any material other than plastic, while it does not have the problems with scuff resistance and potential melting associated with polymers in this application.

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DESIGN CONFIGURATION DETAILS

The potential functionality and basic configurations of the five designs being considered have been established. Also established are the groove dimensions necessary, and the practicality of these grooves has been confirmed by CTA cartridge developer General Dynamics OTS. Of the five designs, only the first three are elaborated on in this report, the first because of its down-selection as the concept to be manufactured and tested in Phase II, and the second and third because of their role as potentially viable back-up concepts.

Nitinol C-Ring Seal Design

The proposed NICRS C-Ring configuration for the CTA application is shown in Figure 1. Similar shaped Inconel seals have demonstrated success with high temperature and high pressure axial blowby in other applications. C-Rings are considered self-energizing because the gas pressure tends to force open the "C" cross-section to further seal the ring against the mating surfaces- the greater the delta-P and therefore leakage potential, the higher the seating force and leakage suppression.

Drawbacks to Non-Nitinol C-Ring Seals:
To MSI's knowledge, metallic C-Rings have not been utilized in ammunition axial cavity sealing applications before. Several reasons for this can be speculated, and are addressed in the NICRS design through the novel use of the smart material Nitinol. The first potential drawback of a C-Ring cartridge seal which MSI has addressed is that metallic C-Ring leakage control is dependent on a tight tolerance interference fit at the groove and bore diameters. In ballistic applications this interference cannot be assured (even maintaining tight manufacturing tolerances) because of the large expansions of the bore. Without a superelastic material such as Nitinol, a C-Ring would not be able to deform sufficiently to provide a positive seal during the combustion process. The second difficulty in C-Ring characteristics that MSI has addressed in Phase I is that C-Ring seals rely on their hoop stiffness to resist the pressure differential. This necessitates a full 360° unbroken ring. Unless a superelastic material such as Nitinol is used, a full ring can not be expanded and snapped into a groove as might be accomplished for a typical piston ring, for example. Therefore, the component onto which the C-ring is installed typically must be split into two parts with a seam placed in the groove. This is not practical for a CTA cartridge because of the extraordinary high internal pressures it must contain.

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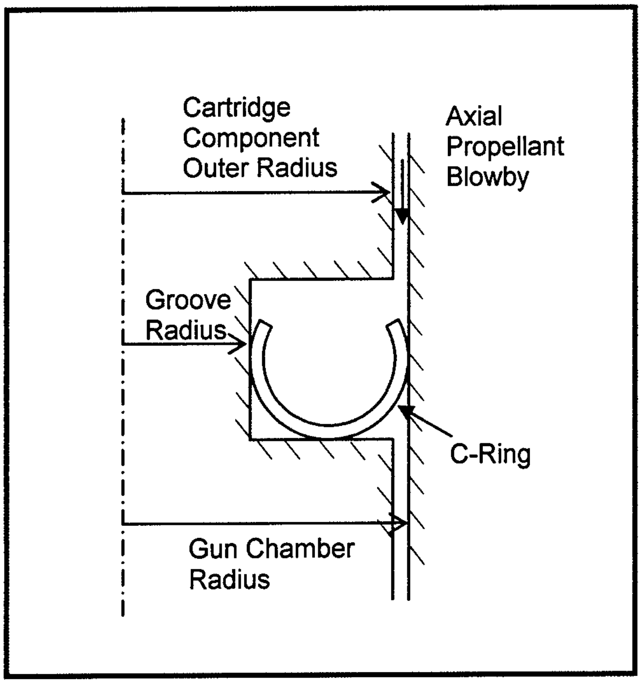

Figure 1. Metal C-Ring Geometry for Ammunition Seal Application

In order to overcome the disadvantages of a typical metal C-Ring, MSI has proposed using Nitinol material for the C-Ring. Either the superelastic or the shape-memory properties of Nitinol, or both, can be employed in order to expand and shrink the ring into a groove thereby circumventing the need for a split cartridge. The other advantage of a Nitinol ring is its superelastic property which allows for greater amounts of expansion together with the swing chamber, with minimal attendant permanent plastic deformation and therefore, along with its "shape memory" property, greater propensity to spring-back after firing. The spring-back behavior should allow for easier cartridge extraction. Unfortunately in the past, traditional fabrication of Nitinol has been considered to be too expensive for applications such as the CTA seal. It is timely and fortunate that, as will be discussed later, MSI's Phase II contractor APC has made significant progress in slashing both the raw material and fabrication costs associated with MSI's intended thin-walled C-Ring configuration of Nitinol in its NICRS seal implementation.

Nitinol Material Behavior:
The following will provide a brief description of the source and action of Nitinol's superelastic and shape memory characteristics. Superelastic means that the material can undergo very large

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non-permanent strains, on the order of 8% in terms of change of length divided by original length. Therefore, a Nitinol ring, for example, under the proper conditions as discussed below can change its diameter by 8%, and then return to its original dimension with no permanent deformation. The term "shape memory" means that a material such as Nitinol is able to be contorted into a dramatically different shape, but when a certain temperature is reached it will exercise strong internal residual stresses in an attempt to return to its original shape. The most important material parameter for the Nitinol with regard to shape memory is transition temperature. Nitinol is Martensitic in crystalline phase when below the transition temperature and Austenitic when above it. It exhibits shape-memory properties when plastically deformed while in its Martensitic phase and then heated to its Austenitic phase. It exhibits superelastic properties when deformed while in its Austenitic Phase.

Combining Nitinol and the C-Ring:
MSI considered the best options to employ shape memory versus superelastic behavior during the installation versus the operation of the seal. There are three different ways that have been explored to assemble the ring to the projectile. MSI's conclusion was that the best method of expanding the ring to assemble it into the groove is to rely on Nitinol's shape memory behavior, because the Martensitic phase of Nitinol, which is present when the material is able to function with its shape memory characteristics, has a lower elastic modulus and it is therefore easier to expand with minimum assembly force. This will reduce the danger of damage to the seal. The metrics of the CTA Tank Ammunition require an operating temperature range from -25°F to 145°F. In order for the seal to have its Austenitic stiff but superelastic capabilities in effect throughout this temperature range, the situation requires a transition temperature somewhat below -25 F. The -25 F transition temperature may be controlled by modifying the precise constituency of the Nitinol. The assembly procedure would therefore require that the Martensitic Nitinol rings be expanded below this temperature and then quickly placed over the cartridge groove so that they shrink down as they heat up.

Other schemes can be devised to take advantage of the Nitinol ring material combined shape memory versus superelastic behavior. Nitinol rings can be stretched super-elastically at room temperature and then allowed to spring-back into the groove. However, with this approach greater care must be taken to prevent damage to the ring because of the higher forces required than for the shape-memory method. An additional approach would involve the shape-memory assembly method being employed at higher temperatures at the expense of having relatively low strength Martensitic Nitinol present during the blowby event. In such a case, thorough testing would be required to ensure that the Martensitic ring is strong enough to seal and not extrude. Finite element stress simulations have been performed for both Martensitic and Austenitic Nitinol, and are presented later.

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To maximize the ability of the NICRS seal to follow the contours of the breech chamber wall, thereby its capacity to seal a worn chamber, MSI has selected the largest ring size that results in an acceptable groove depth in the cartridge. The radial height of the C-Ring was selected at 0.125in and the diameter was sized such that 0.006in of diametral interference occurs at the C-Ring/groove interface and at the C-Ring/bore interface. This results in a groove depth of only 0.111in based on the current size of the Aft Seal as shown in Figure 2. This shallow groove also insures that the Nitinol strains during assemble are below 8%. As discussed below, these groove depths were small enough not to compromise the structural integrity of the components.

For proper function of the C-Ring as the combustion pressure increases, the gas pressure must be able to access the central portion of the "C" cross-section. To enhance this flow path, the ring groove machined into the cartridge outer diameter can be stepped as shown in Figure 2. This is particularly important for the Forward Seal because as the cartridge is introduced into the swing chamber the C-Ring will be pushed axially up against the upstream side of the groove. When the C-Ring is tested (potentially during Phase II of this research), different groove shapes are to be considered. Alternatively the groove can be made without a step and the cross-section of the C-Ring can be modified slightly to enhance the flow path.

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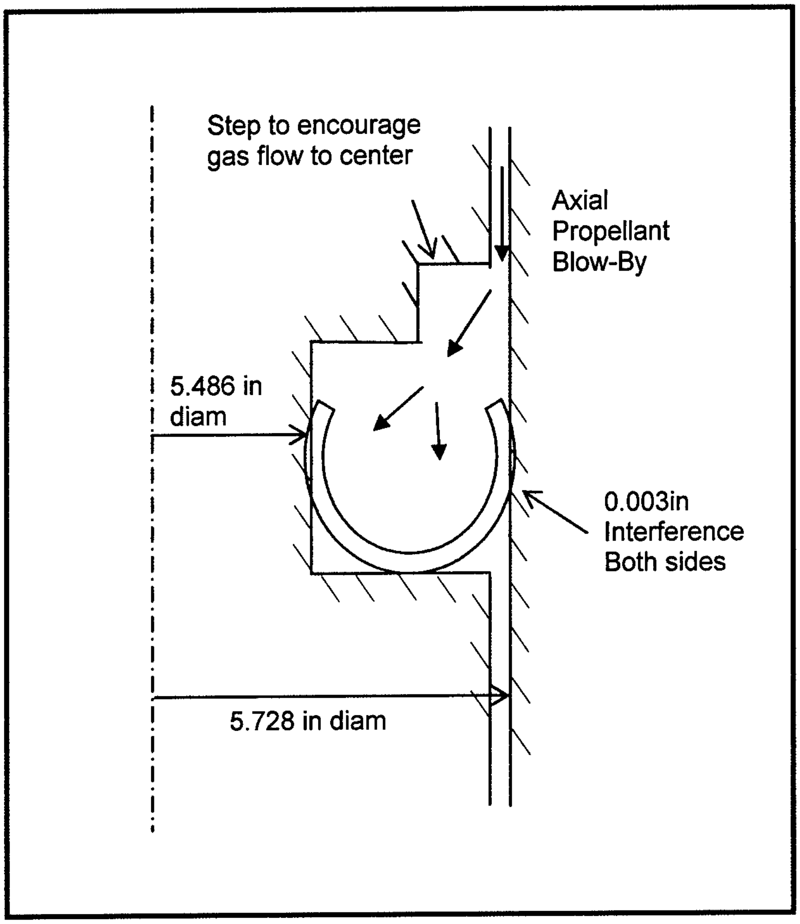

Figure 2. Nitinol C-Ring Cross-Sectional Dimensions

Ballistic Testing of NICRS:
In order to experimentally verify the effectiveness of the NICRS concept, bench and ballistic testing of the first iteration Nitinol C-ring seals is planned during the Phase I Option and Phase II of this research. Prior to fabricating the first Nitinol seals, however, MSI has devised a method of testing the "fit and form" of these seals by substituting relatively inexpensive Inconel for Nitinol, since Inconel COTS seals are readily available. MSI has purchased off-the-shelf Inconel C-Rings manufactured by MSI's Phase II contractor Advanced Products Company (APC), COTS part number ECA-005734-09-14-1-SPN. A photograph of one of these rings is shown in Figure 3. These rings fit the cartridge properly and can be ballistically tested. The rings ordered have a silver coating to provide a softer more ductile outer surface that can improve sealing over any

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imperfections or scratches that may be in the bore. This is a common inexpensive surface treatment for C-Rings, for example in nuclear component static sealing applications.

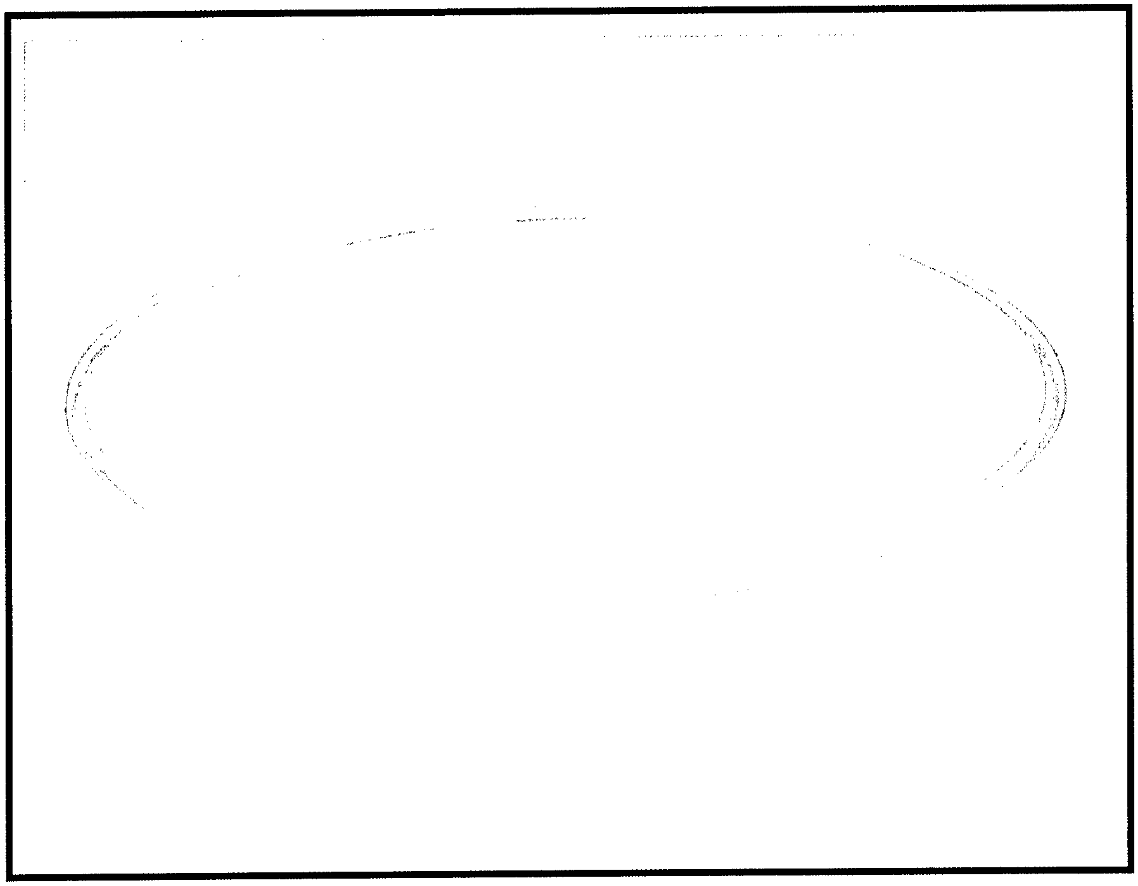

Figure 3. Photograph of Silver Coated Inconel C-Ring Seal. This COTS prototype will inexpensively validate the effectiveness of the C-Ring shape.

The substitute-material seals cannot be elastically elongated such as a Nitinol seal can, and so cannot be slipped over the cartridge end into the seal groove. Therefore, the Inconel seal will be installed by machining away the outer end portion of an experimental cartridge casing, which is in an area thicker than it needs to be to retain the combustion pressure. After the seal is installed, the material that had been machined away will be replaced by a newly machined 4340 (300M) sleeve press-fit behind the seal, returning the cartridge to its original shape. This will not affect operation or structural integrity of the cartridge, because the sleeve will be forced into compression against the chamber by the firing process.

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Teflon/Shape Memory Plastic Ring

The second ranked approach to be investigated, and therefore a back-up seal design, was Teflon (PTFE) or shape memory plastic rings. These rings function in a similar fashion to the metallic C-Rings. The blowby gas pressure forces open the two legs of the ring so that they engage the bore and groove surfaces. A metallic spring is placed between the legs to insure they do not close down prior to pressurization. These types of rings are available off-the-shelf in standard plastic materials such as Teflon. In order to have back-up strategy available for FCS CTA cartridge sealing, during the Phase I Option MSI plans to investigate the possibility of manufacturing these rings out of a variety of elastomers, including shape memory plastic. There are many different varieties of shape-memory plastics based on polyethylene, polyolefins, and fluoropolymers. The expected benefit of using the shape memory material is that after firing, when the seal is acted upon by the heat of the gun tube, the seal can be pre-conditioned to "remember" its previous shape and thereby shrink in diameter, reducing the likelihood of jamming during cartridge extraction. Unfortunately, excess extrusion into the sealing gap (a distinct possibility as described in the analysis section below) would negate the shape memory capability. In addition, a foil coating may be needed to shield the plastic from the high temperature blowby blast, and/ or to protect the outer surface of the seal from unacceptable amounts of damage due to rough handling or environmental exposure. Although such coatings are feasible, they will add production cost and complexity, and will significantly complicate unsegmented-ring seal installation because they will limit the effective "stretch" of the seal available to push it over the cartridge end and into its groove. A partially compensating factor during assembly in the cartridge is that the Teflon seal insertion force is minimized because of Teflon's relatively low friction coefficient (this may enhance extraction as well, if extrusion into the gap is not too severe).

A non-shape-memory COTS Teflon ring has been provided by Advanced Products Company (APC). A photograph of the ring fabricated for future ballistic testing is shown in Figure 4, and a cross-sectional drawing of the ring within a groove is shown in Figure 5. These rings have a cross-sectional height of approximately 0.14 inch and require a groove depth of 0.111in, the same groove depth as for the metallic NICRS C-Ring. The groove depth is slightly longer axially because in order to properly function the elastomeric seal requires more bulk than the Nitinol seal. The diametral interference between the seal and bore is 0.014in which is greater than that of the metal seal, necessarily imposed because the Teflon seal is much more compliant, and at least a minimum surface stress is needed to ensure against blowby during the initial propellant combustion.

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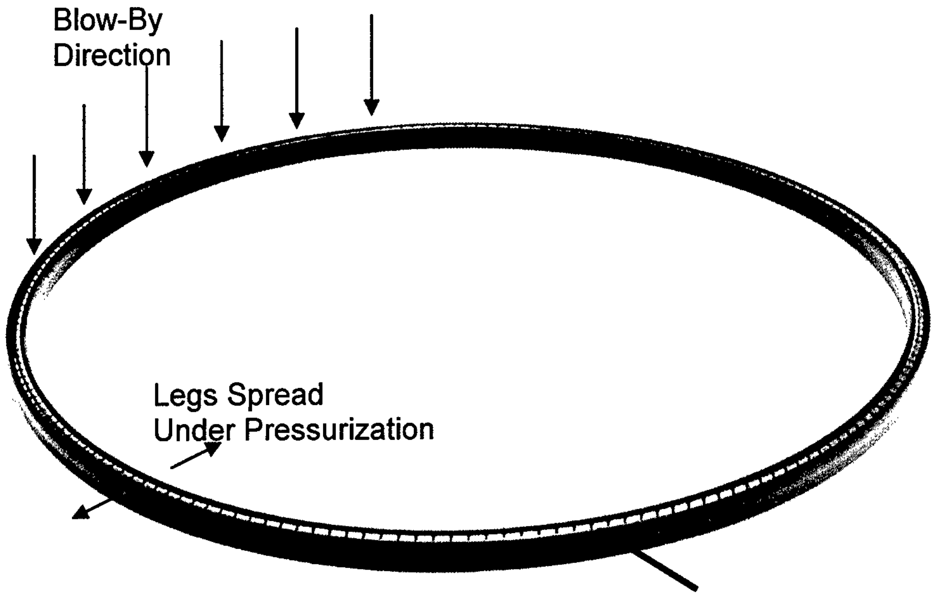

Figure 4. Photograph of Teflon Seal Purchased for First Round of Ballistic Testing

The pressure rating of the Teflon ring is given by the manufacturer as 8000psi for use in a reciprocating or rotating environment. Since the CTA application is a one-time use static environment, much higher pressures possibly can be sealed, although the seal has not been tested to anything close to the 90,000 psi possibly present at the seal in the central cartridge. In addition, there are other important uncertainties involved in the use of any polymeric seal, including dimensional stability, hydroscopic tendencies, low temperature embrittlement, robustness relative to handling and environmental distress, deterioration of compliance or other functionality due to aging, and the potential for melting and/ or gum formation on the bore due to the action of blowby gases. Therefore, the net conclusion is that while the plastic seal deserves consideration as a back-up concept, the Nitinol C-Ring seal will provide more certain sealing, and has fewer hurdles to overcome on its path to prototype development.

Future testing and analysis on the Teflon seal will analytically evaluate the plastic seal as a back-up concept, investigating the effects of both worst case temperature ranges (including accounting for the cartridge remaining in a hot swing chamber for an extended period prior to firing), and worst case blowby circumstances. Also, the effect of bracketing tolerances and resulting

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clearances will be evaluated and tested to determine the extent to which extrusion will occur through the sealed gap between the cartridge outer diameter and the breech chamber bore.

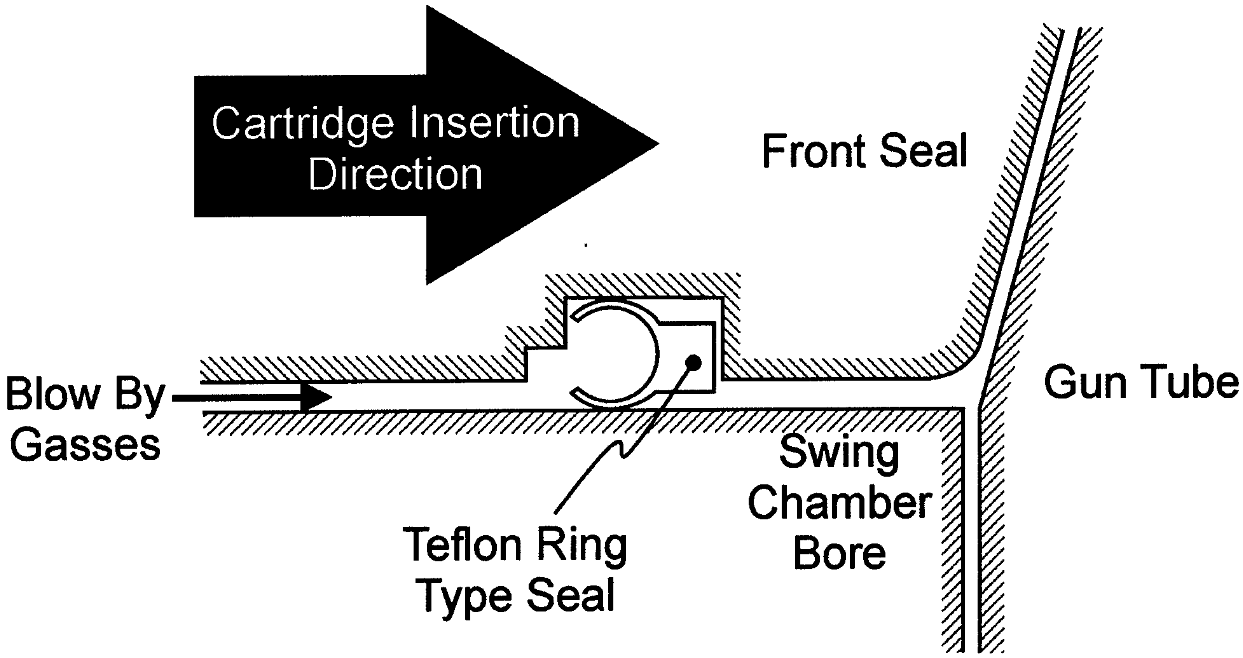

Figure 5. Cross-Sectional Dimension of Teflon Ring Seal

Piston Compression Ring

Based on its success in sealing around cylinders in reciprocating machinery, an obvious option for sealing a cylindrical cartridge's axial blowby condition would appear to be a piston ring type of seal. This choice ranks third among the three most viable concepts that have been under investigation in Phase I. In the CTA cartridge application, a piston ring would function by using the blowby pressure to push the ring outward against the bore and also to push it axially against the axial face of the groove. Unfortunately, typical COTS piston rings of the diameter required for the CTA application (145mm) are too large in cross-section, requiring larger-than-acceptable grooves to be placed in the cartridge. However, during Phase I MSI conceived a ring of adequate strength (Figure 6) that is smaller in cross-section than its COTS cousins. MSI's Phase I piston ring concept is designed with a self-centering chamfer (see piston ring seal cross-section in Figure 7) that automatically compresses the ring in its groove as the cartridge is fed into the swing chamber. The chamfer was designed such that even when the ring edge hangs below the cartridge radial edge due to gravity, the ring should still self insert with acceptable force.

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A drawback of the piston ring concept is that, according to the stress analysis, the minimum required groove depth is 0.135in, which is deeper than the NICRS or plastic ring designs.

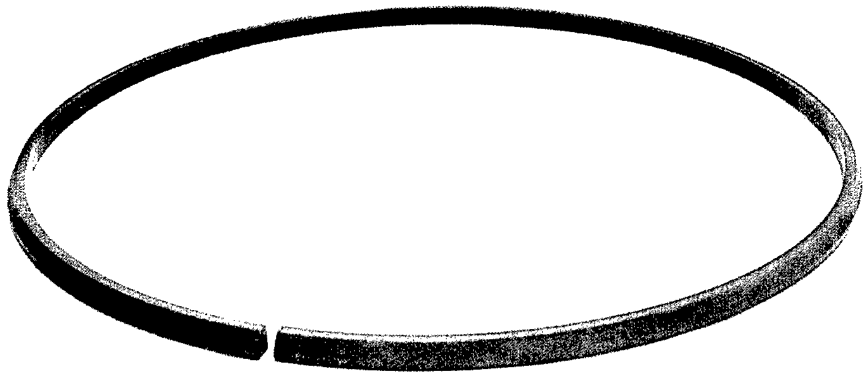

Figure 6. Photograph of Chamfered, Butt-Cut Piston Ring

Another drawback of piston rings is that they must have a gap to provide a "spring out" in diameter in order to seat and function. The gap design depicted in Figure 6 is a standard butt-type gap, used for over a century in internal combustion engines. Although there will be more leakage than acceptable through the but gap, ballistic testing of the COTS ring shown in Figure 6 is warranted. It would allow for investigating the degree of leakage around the rest of the ring periphery, and to observing what other problems (e.g. ring edge chipping or fracture) are encountered during experimental firing. If the idea shows promise then measures can be taken to improve the gap design to reduce gap leakage. Many patented gapless ring designs are available from a variety of manufacturers. Most employ some sort of lap-joint. Figure 8 depicts a gapless lap-joint design provided by Grover Piston Ring Inc. A lap-joint presents manufacturing difficulties for the ammunition application since an ammunition seal that is spread open enough to machine the tongue and groove parts will be spread too wide to fit into the breech chamber.

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Prior to experimental firing another possible drawback should be investigated. The piston ring will tend to tilt under the extremely high pressure associated with CTA propellant combustion, and in the process the ring's edges could act as a forging die to permanently groove the gun tube walls. If the ring edges are rounded in some simple manner to spread out the contact stress, then the resulting ring will no longer perform the excellent sealing present in a diesel engine, for example. Also in a diesel engine lubricant and sliding is present. In CTA ammunition the piston ring will always act at the same location in the gun tube and will possibly create localized wear over time. The worn surfaces of the gun tube can than present sealing problems. It is possible that optimal rounding of the ring edges, and judicious selection of a thick surface coating, could avoid these pitfalls, but there are associated development risks with these.

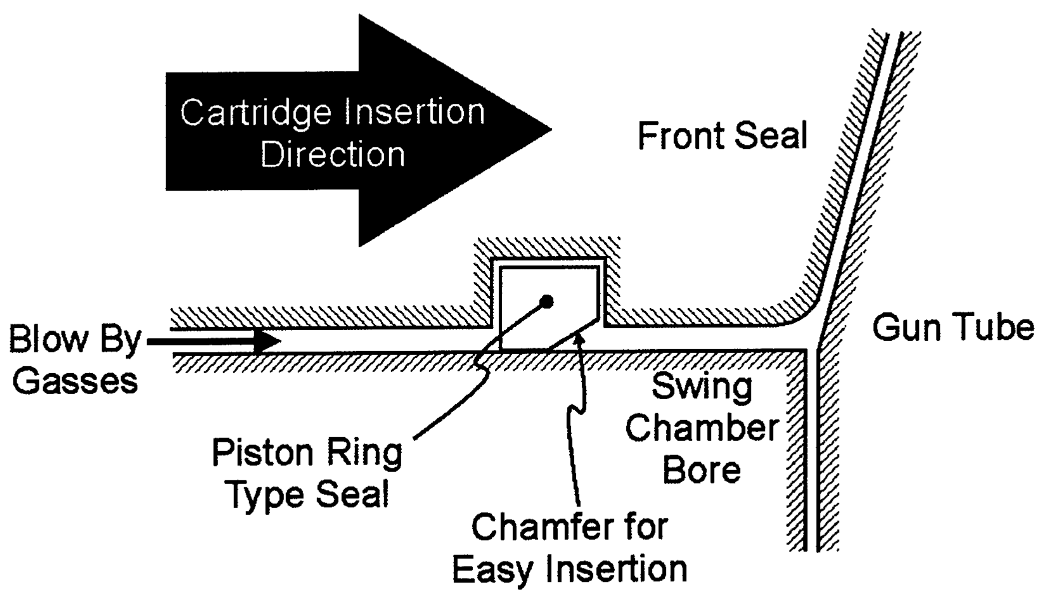

Figure 7. Piston Ring Type Seal Configuration

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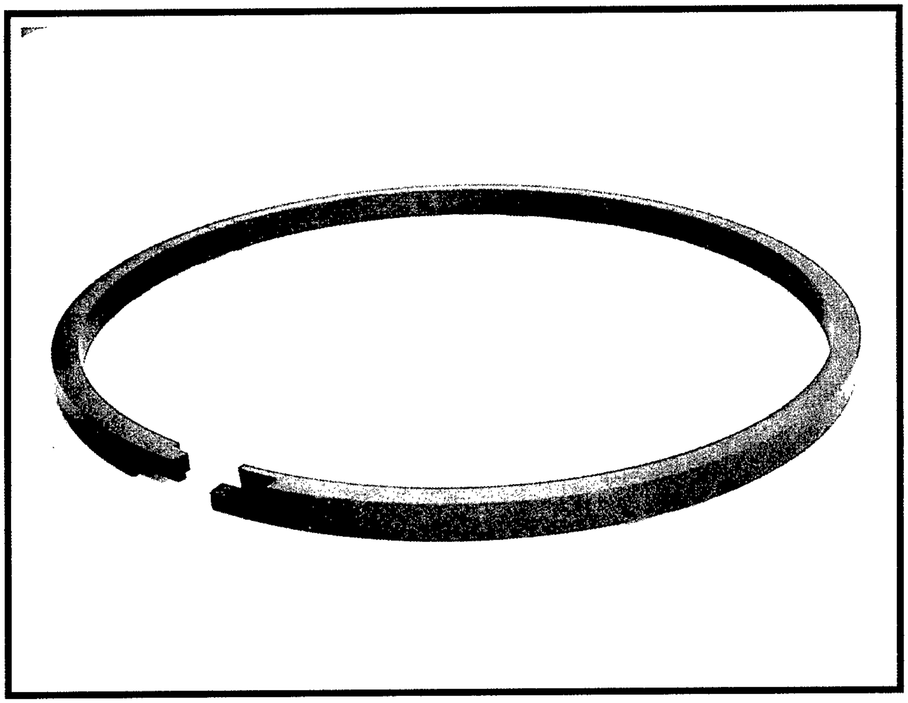

Figure 8. Typical "Gapless" Design. The opposing ends form a tongue-in-groove type of lap-joint seal when the ring is compressed. (Grover Piston Rings Inc.)

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ANALYTICAL STUDY

Stress analyses have been performed on all of the seal designs. Since each design requires modifications to be made to the mating cartridge components, these were also included in the stress analyses. Both the Forward and Aft Seals were considered. Following this analysis, discussions were held with General Dynamics OTS of Red Lion PA, the prime contractor responsible for manufacture of the Forward and Aft Seals. They reviewed the finite element work and are in agreement with the conclusion that the proposed modifications are feasible without compromising the structural integrity of the system.

Full Cartridge Model Results:
Using the computer programs Pro/ Engineer and ANSYS, an axisymmetric finite element model of the entire cartridge system was generated to better understand the stresses and deformations during firing. Shown in Figure 9 is the complete finite element model that includes the forward and aft seals, both the cartridge end pieces (known as the "primary" part of the seal), MSI's sealing concept (known as the "secondary" part of the seal), the casing, and a portion of the swing chamber. An internal pressure of 90ksi was ramped up inside the cartridge to simulate the firing. The stick-slip contact behavior between the components was modeled, with friction included. Correlation was achieved between the finite element model and the ARDEC-provided radial expansion calculation. The gun tube was found to expand radially a maximum of 0.021in as shown in Figure 10. This deflection was on the center of the tube as opposed to at the ends near the seals where the chamber expansion was much less.

Both linear and nonlinear material properties of the cartridge 4340 (300M) material were incorporated into the model. During firing, the forward and aft primary zones plastically deformed, although upon release of the internal pressure they were found to spring back sufficiently to allow for cartridge extraction. This was also in agreement with ARDEC test results. Figures 11 and 12 show the stress distributions in the Forward Seal. For the particular analysis provided as illustration, the seal was grooved to accommodate either the NICRS or Teflon ring design. It was found that the strain associated with the stress in the seals at both ends was well below the ultimate strain allowable for 4340 (300M).

Note that the stress and deformation plot formats are controlled by the ANSYS program used for these calculations. Although ANSYS is an extremely powerful simulation tool, particularly in the full Multi-physics version which MSI owns, its plotting format generally needs explanation. In each case, a spectrum of colors is used to depict the levels of stress or deflection in each portion of the model after loads are applied and contact has reached equilibrium. The plot legend providing the calibration of these colors is given on the right hand side of each plot. For the

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purpose of the use of these plots in this proposal, parameters such as "STEP" and SUB" can be ignored, the logo can be ignored, and only the numbers beside and between each color band need to be referred to. The numbers represent the stress or deflection (depending on plot type as labeled in the figure caption) level that occurs at the boundary between the adjacent colors immediately above and below the respective number. The numbers on the stress plots are psi, and the numbers on the deflection plots are inches.

The point of the finite element stress analysis, and the plotted results provided in Figures 10 through 12, is that the grooving of the cartridge casing to accommodate the NICRS seal does not lead to structural problems. Some stress components such as hoop stress do peak out around the groove as shown in Figure 12. However, potential for failure is determined by the level of all stresses combined, as plotted in Figure 11 using the von Mises stress combination method. Figure 11 shows that the presence of the groove does increase the peak stress beyond that already present in the cartridge away from the groove.

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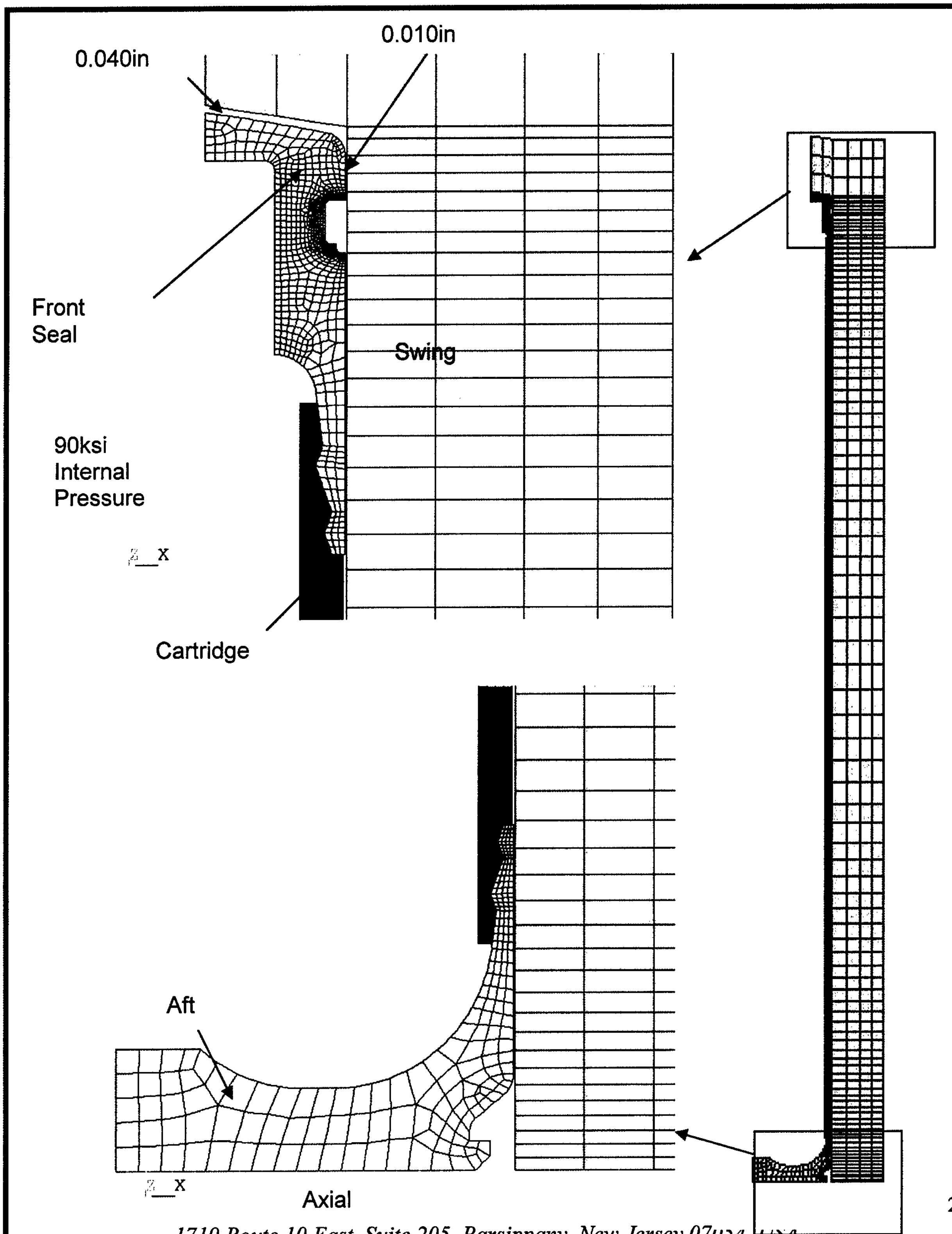

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Figure 9. Finite Element Model and Boundary Conditions for Full Cartridge Model

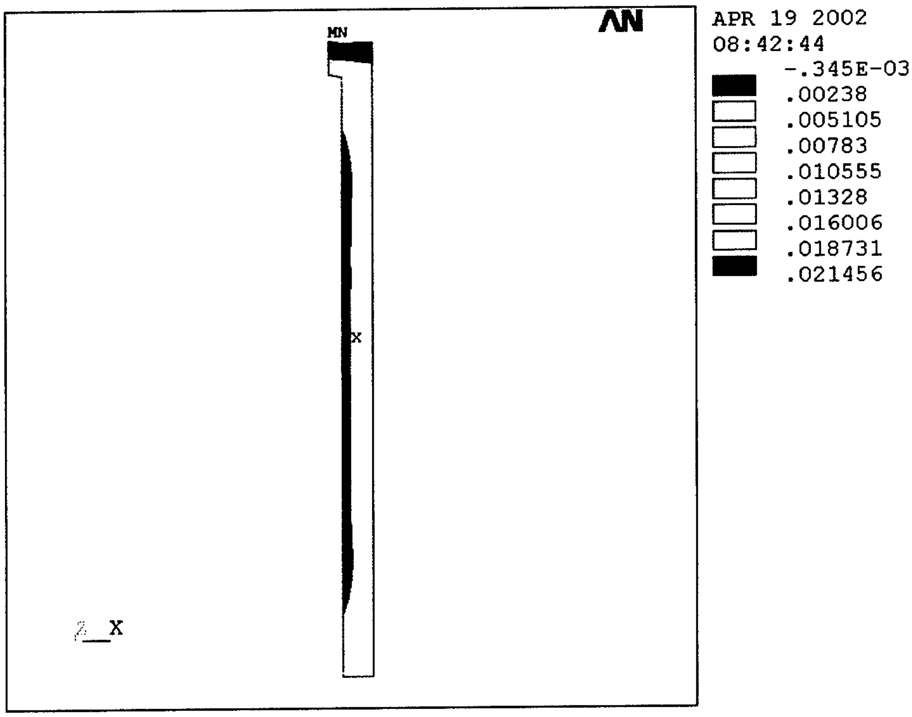

Figure 10. Swing Chamber Radial Expansion in Inches for 90Ksi Cartridge Pressure

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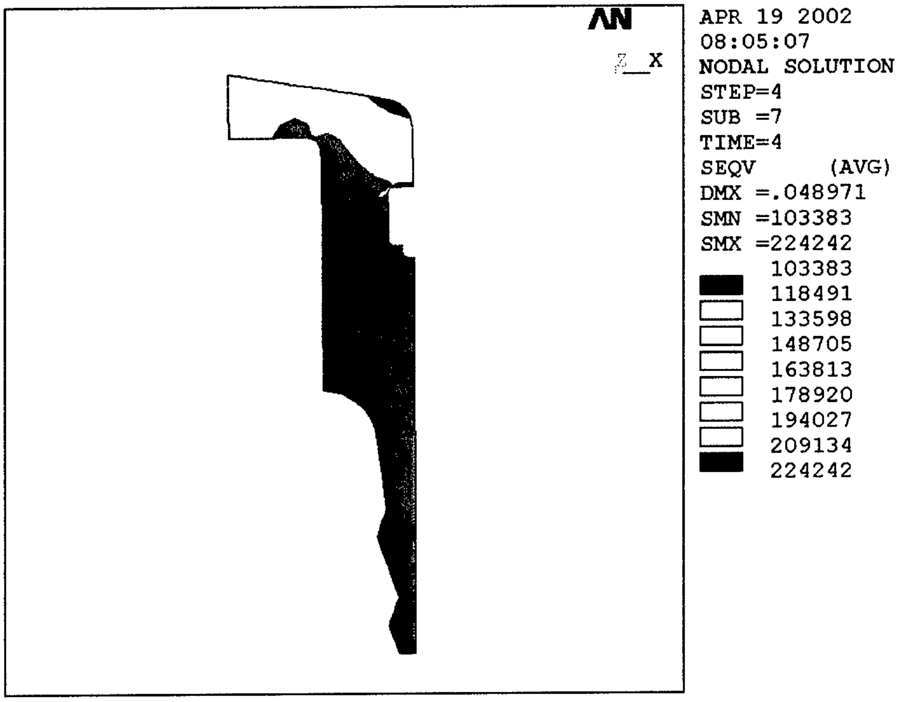

Figure 11. von Mises Stress (psi) in the Forward Seal area due to 90Ksi Firing Pressure

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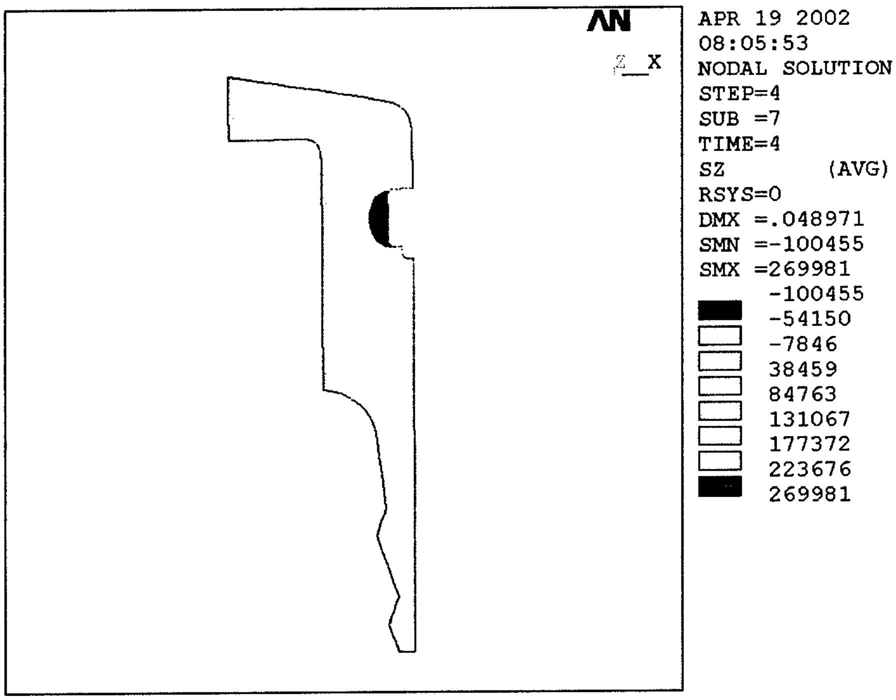

Figure 12. Hoop Stress (psi) in the Forward Seal area due to 90Ksi Firing Pressure

Transient thermal analyses have also been performed on the cartridge system. A temperature vs. time curve was assumed to be of similar shape to the pressure vs. time curve provided by ARDEC. In order to assess the maximum possible effect of temperature, the maximum temperature attained on a worst case basis was assumed to be 3500°F. ARDEC believes that effective temperatures in the annular sealing gap are significantly lower than this worst case number. FEA thermal modeling was correlated to results of test firings detailed in an ARDEC report. Based on this study, it is apparent that the primary factor in stress and deformation levels in the cartridge assembly during the firing event is pressure, not temperature. The most significant effect of firing temperatures is likely to be in the cartridge ejection process, prior to which excessive thermal expansion could encourage jamming of the seal. The effects of thermal processes on the ejection event will be an important consideration in the dimensional optimization that will be performed on the NICRS seal in future research.

Nitinol C-Ring Seal Stresses and Deflections:
As an integrated part of the analysis of the grooved cartridge, stress analysis was performed on the Nitinol C-Ring. Finite element analyses were performed to simulate the effect on the ring of the cartridge assembly process, of the cartridge/ seal system insertion into the swing chamber, of the firing process, and of the post-firing seal extraction. Both Martensitic and Austenitic

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material models were analyzed. The Martensitic model was run to evaluate the situation where the ring temperature during firing would be below the transition temperature. Yield strength, elastic modulus, and elongation (i.e. strain to failure) values for the two different Nitinol conditions were taken from manufacturers' literature. Figure 13 shows the strain in the Nitinol ring due to stretching it to assemble it into the cartridge groove. Since the peak strain is generally below 8% (except for the very upper edge of the SEAL cross-section), and since 8% is marginally within the superelastic capability of Nitinol, the simulation predicts that the ring is expected to spring-back into shape once positioned over the groove. The force required to stretch the ring was significantly less for Martensitic than for Austenitic material. As shown in the figure the ring tends to rotate as it is stretched, in an attempt to minimize its average strain energy (proportional to the area average of stress squared) level.

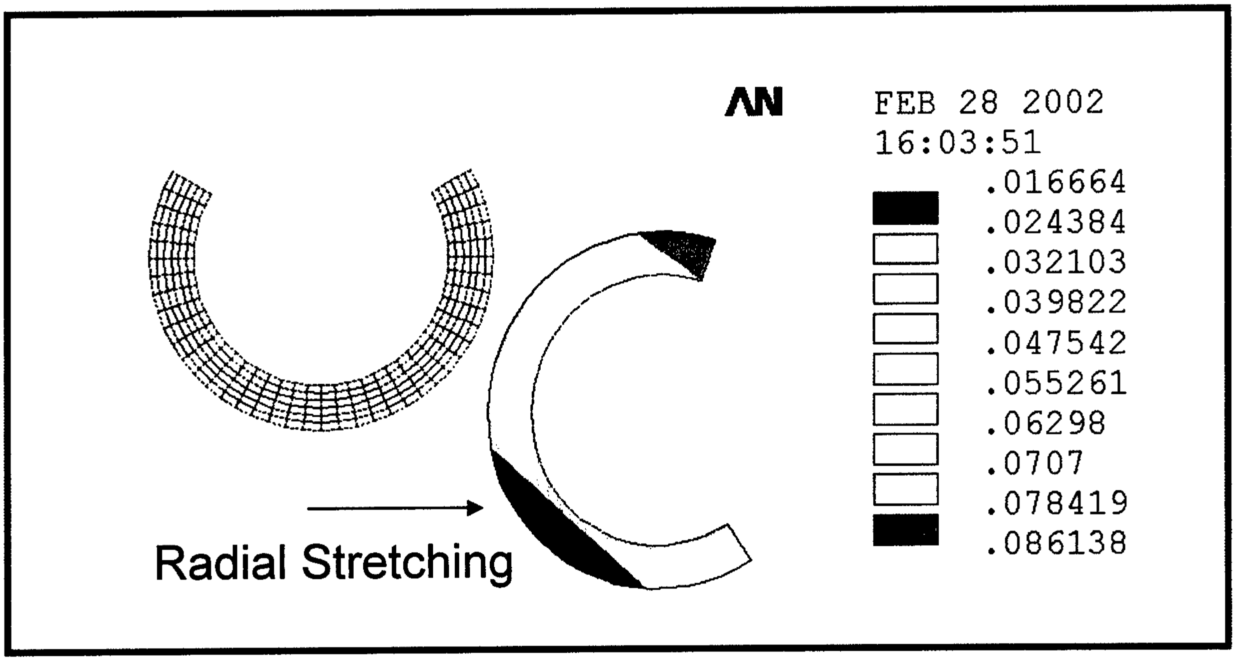

Figure 13. Nitinol C-Ring Strain due to Stretching into Groove

In order to simulate the firing event, an internal pressure was applied to the C-Ring while at the same time expanding the Aft Seal groove I.D. and the swing chamber I.D. For the results shown in Figure 14 (page 20), a worst case 0.021in radial expansion of both the ring groove and the swing chamber was assumed. With an applied blowby pressure of 20,000 psi, the peak hoop strain was less than 8% for the Austenitic ring. As shown in Figure 15 (page 20), the Martensitic ring deformations were greater with only 10,000psi of blowby pressure applied. Results such as these will be obtained throughout the remainder of Phase I and during the early

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Phase II, based on various assembly options and extremes-of-use. These analyses, supported by the increasingly more accurate determination by ARDEC of peak blowby pressures, will determine the optimum transition temperature for the Nitinol seal.

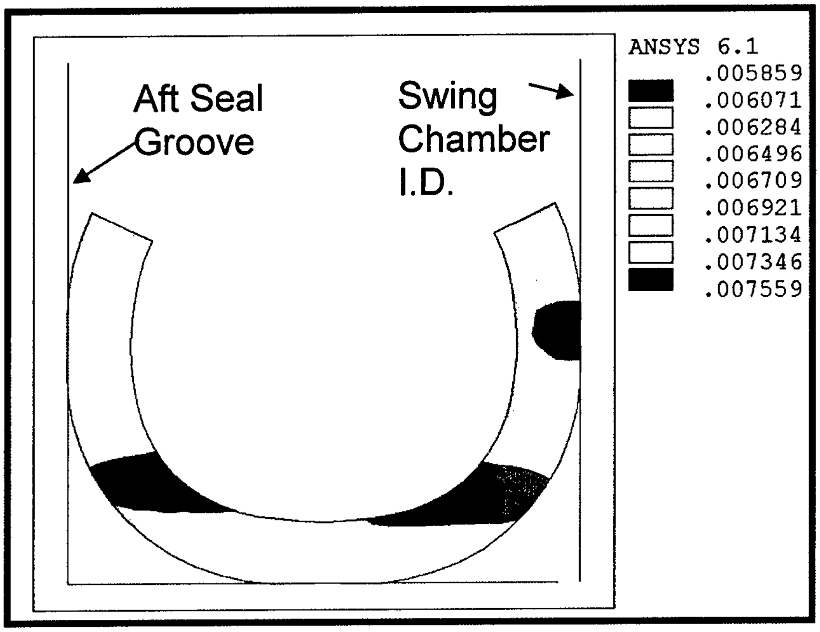

Figure 14. Austenitic Nitinol C-Ring Hoop Strain due 20,000psi Blowby Pressure and Worst Case 0.021in Radial Expansion of Aft Seal And Swing Chamber

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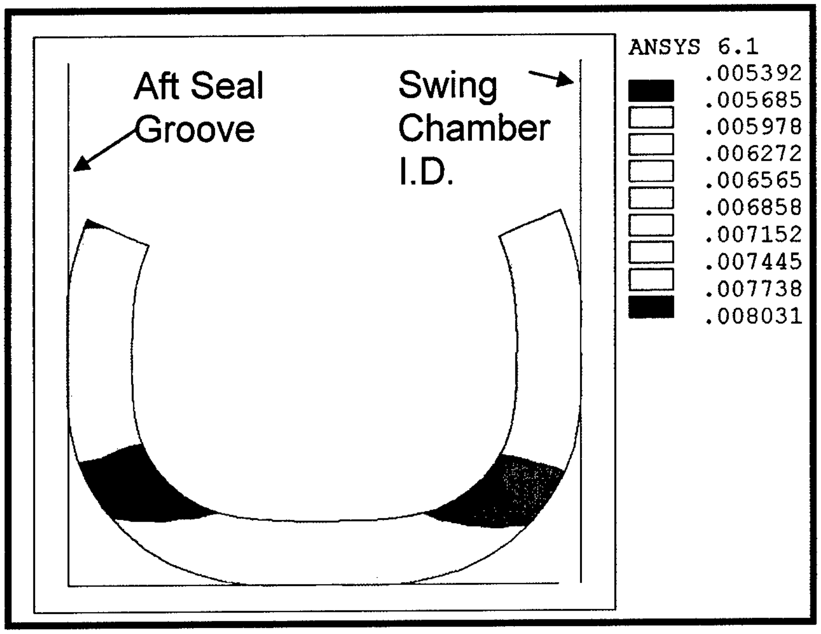

Figure 15. Martensitic Nitinol C-Ring Hoop Strain due to 10,000psi Blowby Pressure and Worst Case 0.021in Radial Expansion of Aft Seal and Swing Chamber

Teflon Seal:
The main issue to guard against for the elastomeric ring is extrusion. While manufacturer data is somewhat encouraging in this regard, this is primarily because the firing event is so brief. Fundamentally, any plastic seal material is expected to behave as a "Bingham plastic", with a finite shear strength, and an effective viscosity once the shear strength has been surpassed. The extrusion-resistance of the various plastic materials under consideration will not depend so much on their shear strength, which is far too low to provide much resistance to the worst case combustion blowby pressures, but from the effective viscosity component. The shear stress (and therefore pressure) required to extrude a Bingham plastic of relatively low shear strength is roughly proportional to the speed at which the extrusion process is to take place, divided by the gap width. Since the firing process is on the order of 10 milliseconds based on ARDEC data, the amount of force required to extrude most of the seal material through the cartridge O.D./ swing chamber I.D. gap appears greater than even that available from the full combustion pressure.

Concerning the effect of the plastic seal's groove on the overall cartridge design, MSI's discussions with plastic seal manufacturer APC determined that it was practical to manufacture a

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seal with a cross-section as small as that of the NICRS seal. Therefore, the analysis of the groove in the case of the NICRS seal would apply to the plastic seal as well.

Piston Ring:
Similar to the NICRS concept, the piston ring stress was analyzed while acted upon by the blowby pressure. Of particular importance for the piston ring is the maximum shear stress near the edge of the sealed cavity. For a blowby pressure of 90ksi the peak shear stress was approximately 32ksi. Materials typical of piston rings such as high quality grey cast iron or ductile iron can withstand this pressure without fracture, although with any relatively brittle material there is always a finite chance of fracture, with attendant scoring of the swing chamber I.D. Therefore, a certain population of piston rings are likely to fracture, causing wear and leaving pieces of ring in the gun tube. This problem might be addressed by a change to a ductile material, but ductile materials have historically not performed well as piston rings, being subject to deformation into the leakage gap, and jamming. This could be addressed by use of a superelastic and shape-memory material such as Nitinol, but a solid piston ring made of Nitinol would be cost-prohibitive relative to raw material alone, regardless of fabrication cost. The NICRS concept uses a very thin, hollow C-ring of Nitinol, using a fraction of the material per seal that a piston ring would require.

In addition to this shear stress, cocking of the ring is possible if the sharp corner catches on an asperity on the ring groove sidewall. This implies that special (expensive, and possibly impractical to manufacture) contouring of the piston ring would be required minimize interface stress along its edge.

The cross-sectional size of the piston ring which was considered, needed to be a bit larger than that of the C-ring or the Teflon ring. This larger size necessitates a larger groove. The larger groove was analyzed similarly to the other designs and the stress and strain levels in the Forward and Aft Seals were found to be acceptable.

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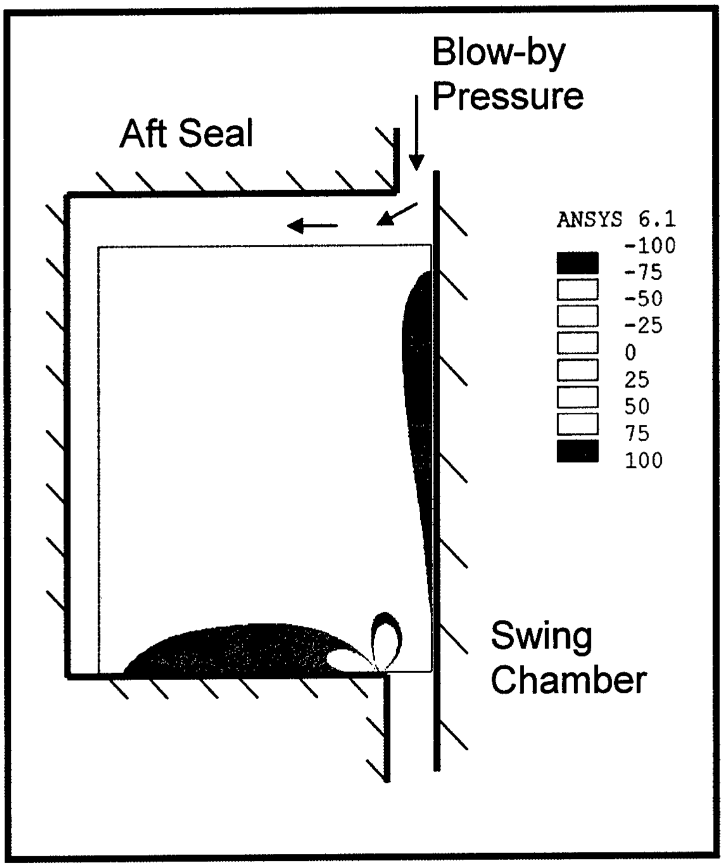

Figure 16. Shear Stress within Piston Ring for 90ksi Blow-by Pressure (MPa)
Note that the gray areas in the contours represent stresses in excess of 100MPa (14.5ksi).

Rubber Skirt:
A stress analysis was performed on the rubber-skirted cartridge assembly with an internal pressure applied. Since recent ballistic testing of this design resulted in frequent cracking of the cartridge casing, this analysis was primarily to develop an understanding of the pressure distribution in the cartridge case as well as the deformation behavior in the rubber. It was found that with the standard rubber skirt design the nearby cartridge case experiences much higher bending stress than for non-rubber skirted designs. This was because the rubber provides little constraint to the cartridge case expansion. In order to further assess this effect, a modified rubber seal was analyzed. This modified design applied rubber only to the outside surface of the forward seal . This gave support to the casing during pressurization and dramatically reduced casing stresses in the area near the seal. At an internal pressure of 1000psi the standard skirt exhibited stress levels near 5ksi whereas the modified design was approximately 3.5ksi. Based

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on this understanding of the casing deformation the rubber skirt design can potentially be optimized by somehow increasing the casing radial support. This can be done by potentially reducing the air gaps around the rubber and relying on the high Poisson's ratio of the elastomer to provide support. This analysis also lends credence to other concepts being considered such as Nylon 11 coatings to be applied to the forward and aft seals.

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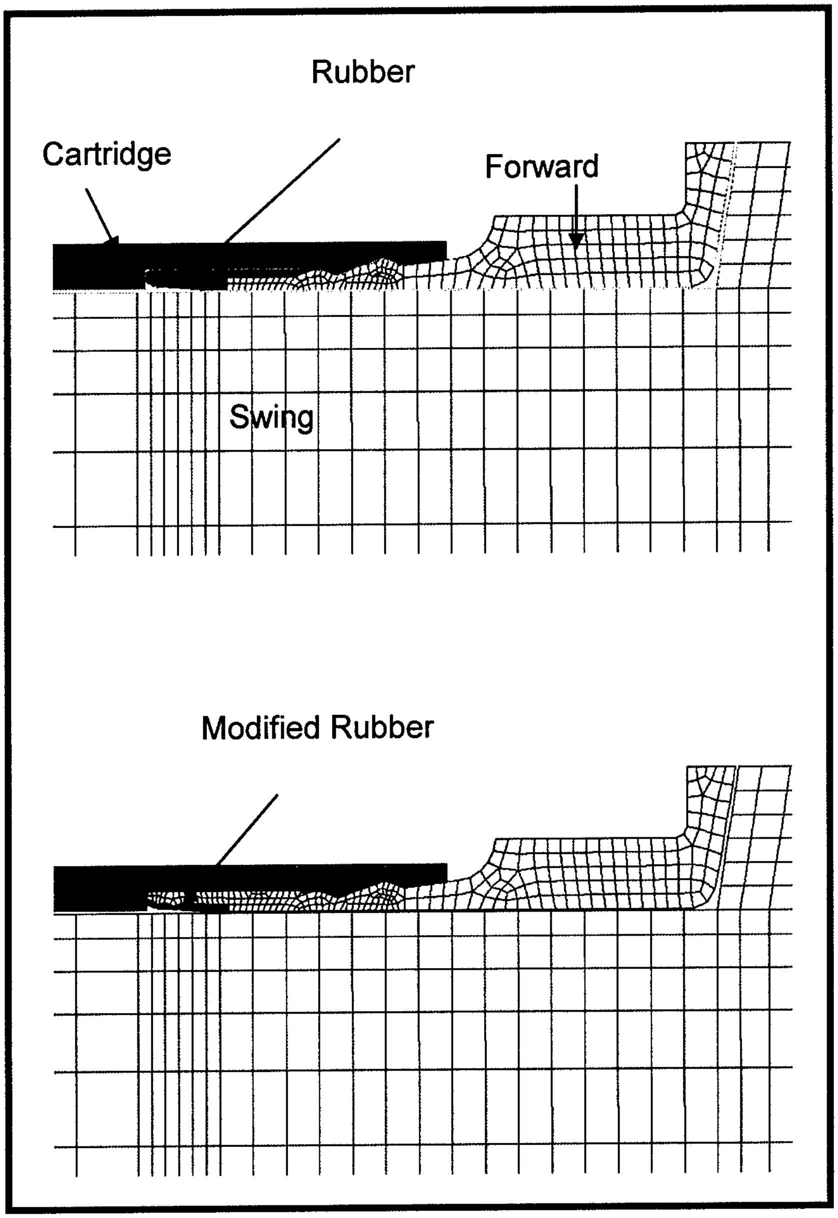

Figure 17. FEA Models of the Standard and Modified Rubber Skirt Design

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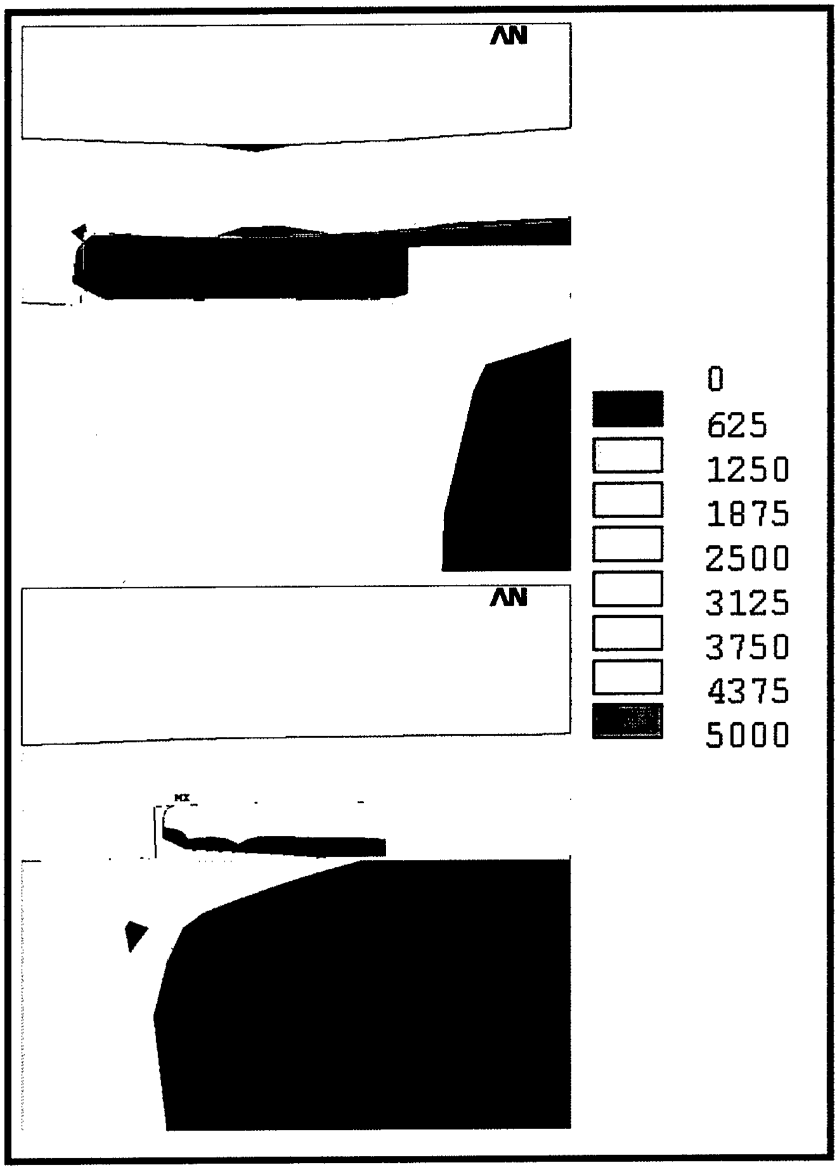

Figure 18. von Mises Stress (psi) Standard and Modified Rubber Skirt
1000psi Internal Pressure Applied

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MANUFACTURING STUDY

Nitinol C-Ring Design

MSI along with Burpee Materials Technology, LLC (a contractor during Phase I) devised a potential method for manufacturing prototypes out of Nitinol rod stock. This process, developed by Phase I consultant Janet Burpee, involves heat treating the rod, forming it into the closed circle, welding the ends together, annealing out any residual stresses, and finally laser cutting the "C" cross-section. So far no prototypes have been made using this method. One of the difficulties with the Burpee method will be keeping the tight tolerances required. In addition, it is apparent that the material scrap and production costs for such a process are likely to be quite high. On an experimental basis, these prototypes could be used to validate the shape memory or superelastic methods to be used for assembly into the groove. However, because of the prohibitive projected production cost, during Phase I of this project MSI searched for a superior manufacturing process. A promising fabrication procedure was offered by the leading C-Ring seal manufacturer, Advanced Products Company (APC). APC is already pursuing research, independent of this Phase II proposal, into the innovative construction of Nitinol C-Rings, as described below. The basis for APC's work, and the likelihood of their success, is the fabrication procedure that they already use for Inconel C-ring seals, which APC manufactures on a regular basis. Like Nitinol, Inconel is a material which is very difficult to fabricate in thin non-flat cross-sections.

The key feature in APC's proposed reduced-cost Nitinol seal production is a new method of fabricating Nitinol as a thin-strip raw material. In thin-section Nitinol component production, a major concern is the cost of the strip form of raw material, which with today's technology costs approximately $1000/lb. APC is collaborating with ProMet Technologies (PTI) of CA on a Phase II SBIR project for the Navy that is developing a manufacturing technique that appears to have been successful in dramatically reducing the cost of the strip form Nitinol. Material made with the new process in not cheap (roughly $200/ lb), but given the low weight of MSI's seal will allow the combined material, fabrication, and overhead costs to total under $5 per seal, versus the Army's current target of $10 per seal (At $5 each, material cost for the new method of Nitinol sheet fabrication would be about half of the total seal cost).

The remainder of the cost (and manufacturing process development challenge) for a Nitinol C-Ring seal is the forming of the ring shape, the joining of the ring ends, and the coating of the ring with a "conformable" coating of solid lubricant, such as silver. The forming, welding, and coating techniques necessary for manufacture of a Nitinol C-Ring are already performed on a regular basis by APC for Inconel C-Rings. However, an achievable challenge in Phase II will be to adopt these procedures to Nitinol, and to optimize them for cost competitiveness. Based on the research performed by APC to date, it is clear that the issue will not be whether the making of

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NiTi rings is achievable, but rather how low the cost can be driven. APC and their supplier ProMet will collaborate with MSI in establishing large scale manufacturing costs, as well as in making the prototype parts.

De-Selected Back-up Designs:
The Teflon rings in the form investigated during this Phase I project are essentially an off-the-shelf design, manufactured by APC. APC approximates large scale production costs in the $5 per part range. Such a cost would be superior to the present Army cost target of approximately $10 each in quantity. Although the material cost is much less than Nitinol, the built-up design of the seal (plastic surrounding a spring) increases cost, and the need to shelter the seal surface from handling, the environment, and combustion effects will require some form of wear resistant/ corrosion-resistant metal coating or foil cover. The assembly of such a metal-surface-protected plastic seal in turn raises assembly issues. The spring-cored, flexible plastic seal in its COTS version in principle can be stretched into place over the cartridge end into its groove. However, in its bench test assembly trials of prototype plastic seals stretched over the ends of actual cartridge cases, MSI experienced permanent deformation of the plastic/ spring core assembly, such that it would bulge out of its intended groove. Perhaps such a seal can be reverse-deformed into the groove with application of pressure and heat, for example. However, any wear resistant metal coating or foil will not be as flexible and low-heat-formable as the plastic and therefore will either rip, or will make the post-fit permanent deformation situation worse. To overcome this issue, MSI conceived of a superelastic metal such as Nitinol being used as the outer cover for the plastic, and has written a third patent disclosure concerning this idea. However, if Nitinol foil coats the plastic, then this increases material costs, and begs the question of why not simplify the seal, and make it solely out of the Nitinol. Therefore, the overall production costs and difficulties discourage the use of a plastic seal.

Piston rings of the design described above, with no provision for a zero-leakage gap, are available inexpensively as ductile iron COTS items. Manufacturing difficulties with standard butt-gap piston rings have long since been worked out by the automotive industry, and other users of reciprocating pistons. Such rings were quoted at $5 per part for small quantities (<250), and in reasonably large quantities would cost about $1 per part. Unfortunately, given the very high pressures associated with propellant combustion, a sealed-gap or a "gapless" design is necessary. Manufacturing techniques would need to be developed for this, and it is likely that the cost of the ring will increase to over the $5 each level if the following design and application issues are addressed in any piston ring prototype:

1. Tongue-in-groove or similar type complex ring gap is need to prevent blowby. Besides the extra cost of machining a tongue-in-groove rather than a flat or beveled gap, the problem of fabricating the ring such that the tongue is inside the groove when the ring is

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not compressed can only be overcome by in-place machining of the tongue out of the groove, for example by electro-discharge machining (EDM) or laser machining. While such processes have dropped in price in recent years, they would still make production costs prohibitive. While NICRS fabrication procedures also pace cost of the seal, once processes (as discussed elsewhere in this proposal) are optimized, APC estimates costs of less than $5/ seal in quantities of 50,000 per year or more.

2. The piston ring in a reciprocating engine, as well as the opposing bore, cannot seal the combustion gases without the aid of a thin film of lubricant between the ring and the cylinder. Such a film is not present in the proposed cartridge seal application, unless it is added through some form of solid lubricant. Although a thin solid lubricant could work if the piston ring surface was elastically "conformable" (i.e. could easily deform to match the shape of the opposing wall), it is not, and as the breech chamber wears the resulting uneven-ness will require a very thick solid lubricant coating to seal the local surface imperfections. Even if the breech chamber wears evenly (unlikely), the larger diameter of a worn chamber will require the piston ring to spring out further than it's design diameter, causing it to ovalize. Again, in the reciprocating engine, such a situation is overcome by the lubricating oil film, at least until wear has progressed beyond the capacity of the viscous oil to compensate. In a gun tube, to provide enough compensation with, for example, a silver coating would require a coating too thick to be maintained on the ring surface unless it were handled with great care during manufacture, shipment, and field usage. Such a constraint would be impractical. The NICRS seal is able to function without thick solid lubricant coatings because its sealing is provided by a thin wall of Nitinol, which will elastically deform to follow worn areas of the wall and other imperfections.
3. Standard piston rings do not need to deal with the extreme pressures that the proposed seal would encounter in the worst case. Even so, these seals "roll" (i.e. a cross-sectional view shows them "tilt" relative to the piston centerline) to some extent, potentially digging into the cylinder wall. In large part, in an engine this is prevented from happening by the lubricant film which limits the local surface contact stress between the rolled edge of the ring and the cylinder wall. Again, the lubricant film will not be available in this case on the cylinder wall. In addition, the much higher pressure faced will significantly rotate the ring, encouraging it to act as a forging tool, indenting the breech chamber wall. This process can be prevented if the ring O.D. is carefully contoured along the ring axis, rather than being merely flat or beveled in the cross-sectional view. This will once again increase cost, and it might not be practical to consistently perform the manufacturing of such a contour to the tight tolerances that would be required to keep edge stresses sufficiently low, based on Phase I studies. Since the Nitinol C-Ring has a roughly round cross-section and is relatively conformable, such tight tolerancing of surface shape is not required for NICRS.

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CONCLUSIONS AND RECOMMENDATIONS

1. In Phase I of this project, MSI initiated and evaluated 8 concepts through modeling and simulation, in combination with limited manufacturing and testing, consistent with its original proposal to the Army. The results of Phase I indicate that the superior concept is a Nitinol (NiTi) C-Ring Seal assigned the acronym NICRS (pronounced "knickers").

2. The NICRS sealing concept is a feasible design concept for the CTA gun seal. Based on intensive finite element analysis it was found that the seal can indeed stretch enough to be assembled onto the cartridge and also dilate with the gun chamber during firing. It can potentially withstand significant pressure and also spring-back after firing for easy cartridge removal.

3. The NICRS seal, being metallic, will be less susceptible to environmental effects than conventional elastomeric type seals. NiTi material is very resistant to wear, erosion, and corrosion.

4. The configuration of the NICRS seal also will lead to a better stress distribution in the cartridge case than a conventional rubber skirt design. The rubber skirt was found to allow high bending stress in the casing due to the lack of radial support in the skirt area.

5. A groove must be placed into the cartridge component in order to accommodate the NICRS seal. This groove will not create any structural problems in the cartridge component (forward or aft seal).

6. The shape memory effect is best taken advantage of for assembly of the seal into the groove. The superelastic effect is to be utilized for the sealing function during the large expansion and spring-back of the gun tube.

7. TACOM-ARDEC should ballistically test the NICRS concept as well as other viable concepts that were investigated by this research, such as the piston ring, the Teflon ring, and the rubber skirt.

8. The conventional rubber skirt seal concept was found conceptually acceptable, but results in higher casing stresses due to the lack of radial support of the casing where it is surrounded by the skirt.

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